

# **Implementation and Research on the Operational Use of the Mesoscale Prediction Model COAMPS in Poland**

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## **LONG-TERM GOALS**

Our long-term goal is to implement an operational high-resolution atmospheric data assimilation and prediction system and to use it for daily weather forecasting. To date we have worked on several operational and scientific aspects of the problem using the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®<sup>1</sup>): (a) setting up stable large scale data transfer capabilities to facilitate COAMPS runs 2-4 times per day in an operational manner for different geographical regions and using different nested grid configurations; (b) perform research on the MPI scalability of COAMPS on selected computer architectures and to optimize the code to take advantage of the vector capabilities of the Cray X1 and the massively parallel features of our Linux cluster; (c) identify and understand the uncertainties in high-resolution NWP forecast and their impact on severe weather, such as extreme rainfall, and to develop model metrics appropriate to mesoscale weather phenomena; and (d) improve our knowledge of observational error characteristics for spatially correlated data and develop the numerical schemes capable of assimilating these types of observations.

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<sup>1</sup> COAMPS® is a registered trademark of the Naval Research Laboratory.

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## **OBJECTIVES**

The objectives of this project are to: (a) implement an operational data feed from the Navy Operational Global Atmospheric Prediction System (NOGAPS), and implement a semi-operational version of COAMPS at the Interdisciplinary Centre for Mathematical and Computational Modelling (ICM), Warsaw University; (b) validate COAMPS model performance through inter-comparisons with statistics obtained from the United Kingdom Meteorological Office (UKMO) unified model; (c) investigate the scalability of COAMPS on ICM computers, a 200-processor OPTERON cluster and a Cray X1; and (d) develop a data assimilation scheme that can assimilate remotely-sensed and non-conventional data sources with a special emphasis on Doppler radar data. Meeting these objectives will allow the Polish National Air Defense to issue 1-5 day mesoscale weather forecasts in the regions of their interest, including Poland and Central Europe.

## **APPROACH**

Our approach is to utilize NOGAPS for initial and lateral boundary conditions, and COAMPS for mesoscale atmospheric forecasts. The NOGAPS fields are obtained from the Global Ocean Data Assimilation Experiment (GODAE) server at the Fleet Numerical Meteorology and Oceanography Center (FNMOC) and transferred to ICM in automated (machine-controlled) efficient and stable way, thanks to support from FNMOC. We ported the COAMPS system to the ICM Linux cluster and Cray X1 computers and measured system performance and scalability using tools developed in-house for model verification. The unique aspect of our capabilities is that we concurrently run the UKMO mesoscale model on a grid that is similar to the one used by COAMPS. We will also investigate the time evolution of the conditional forecast (background) error probability density function using an ensemble of the model forecast to generate background error statistics. This helps us to identify and understand the uncertainties in high-resolution NWP forecasts on high-impact weather, particularly extreme rainfall. Finally, we will study observational error characteristics of radar reflectivity and radar radial winds. Such observations have the potential to provide detailed information to improve mesoscale analyses and forecasts. We will study historical weather events for which we have radar data to understand the observational error characteristics. We will investigate how they may be applied in data analyses used for assimilating radar data into numerical weather prediction models.

## **WORK COMPLETED**

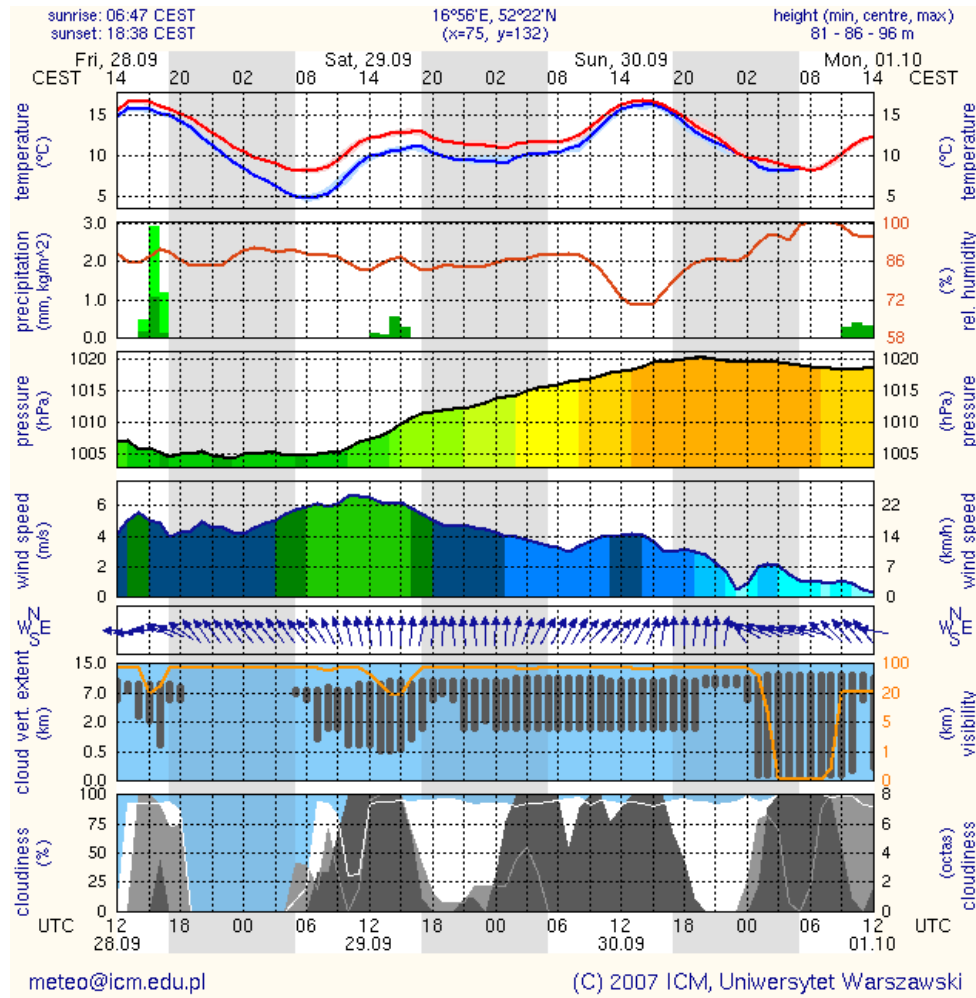
During FY07 we accomplished the following tasks: (a) made a revised set-up of the US Navy COAMPS system on ICM machines at Warsaw University for the purpose of providing operational support to the general public using the ICM meteorological web page, (b) improved some parts of the COAMPS system (more frequent boundary conditions, variable step in interpolated boundary data), (c) improved the optimal interpolation analysis of sea surface temperature and sea ice data by introducing sample dependent correction of the background error covariances, (d) investigated the correlation of errors in radar reflectivity data using historical data from Baltex Radar Data Centre, (e) worked on the development of the entity based approach to the verification of precipitation patterns predicted by the COAMPS system, and (f) worked on the development of the ensemble Kalman filter approach for the purpose of assimilating radar reflectivity and radial wind data in COAMPS.

## **RESULTS**

During FY07, we sufficiently increased the frequency of lateral boundary conditions transmitted from the GODAE server to our model domains. Using the COAMPS restart capability, we implemented

three restart runs with different frequencies for the interpolation of lateral boundary conditions (LBC). For the forecast period from 0 to 24h we used LBC data in 3h intervals, for the period from 24 to 72h we used LBC data in 6h intervals, and for the period from 72 to 120h we used LBC data in 12h intervals. These changes in LBC frequency resulted in improved prediction of selected meteorological elements, such as more accurate prediction of the position and intensity of low and high pressure centers, and more accurate prediction of precipitation patterns. We also introduced some changes into the configuration of our model domains. Two independent domains of our forecast were designed. The first one, called NAE, covers the North Atlantic and European area, and consists of 3 nested grids with different spatial resolutions and forecast lead times. The coarse grid has 193x127 grid points with a mesh size of 39km and lead time of 120h; the second one, placed over Central Europe, has 169x217 grid points with a mesh size of 39 km and lead time of 72h; and the third one, placed over Poland, has 193x175 grid points with mesh size of 4.3 km and lead time of 48h. Our second domain, called ME, covers Middle Eastern countries, and consists of two nested grids. The coarse grid has 117x71 grid points and a mesh size of 45 km, and the inner grid has 259x127 grid points and a mesh size of 15 km. Both grids have lead times of 72h. This domain is used to support military activities of Poland in NATO and UN operations.

The official web page of the COAMPS model at ICM has been rewritten and tailored to the needs of our general public users. The page consists of two types of presentations: maps of selected meteorological elements over the second (13 km) grid of our NAE domain presented in 3h intervals until 72h, and the meteograms for selected cities within the same region. The user has the option to choose any point in the region. An example of such a meteogram is shown in Fig. 1. The time series in 1h intervals shows the temperature, humidity, rain, mean sea level pressure, wind speed and direction, cloud vertical extent, and amount of cloudiness in three levels (high, medium, and low clouds) in separate panels on the diagram. This presentation of the results of the numerical weather forecasts is very popular among our users.



**Fig. 1.** Example of the meteorogram constructed from COAMPS forecasts for the 13 km, Central Europe grid. Data are presented in 1h intervals.

In addition to this official web page ([http://new.meteo.pl/index\\_eng.php](http://new.meteo.pl/index_eng.php)), we have also developed a second web page (<http://coamps.icm.edu.pl>), where selected results, both at the near surface level and at few levels in free atmosphere are presented for all nested grids for both the NAE and ME domains.

During FY07, we worked also on improvements to the COAMPS data assimilation. The COAMPS analysis is based on the multivariate optimum interpolation (MVOI) analysis scheme described in Goerss and Phoebus (1992) and Barker (1992). The MVOI technique uses observational data to compute increments for the first-guess fields from either COAMPS or NOGAPS. The analysis variables for the MVOI are geopotential height, and the u and v wind components. The first guess fields are adjusted based on observational data via a MVOI analysis. The analysis computes height and momentum increments based on differences between the first guess fields and the observations. The COAMPS system also has an ocean analysis component – the NRL Coupled Ocean Data Assimilation (NCODA) system (Cummings, 2003). We utilize the 2-dimensional option in NCODA to provide updated sea surface temperature and sea ice concentration for the COAMPS lower boundary conditions. The analysis background is generated from the previous NCODA analysis. NCODA computes corrections to the first-guess fields using all the observations that have become available

since the last analysis was made. A complete derivation and description of the MVOI method used in NCODA is provided in Daley (1991). Essentially, the MVOI problem is formulated in NCODA as

$$\mathbf{x}_a = \mathbf{x}_b + \mathbf{P}_b \mathbf{H}^T (\mathbf{H} \mathbf{P}_b \mathbf{H}^T + \mathbf{R})^{-1} [\mathbf{y} - \mathbf{H}(\mathbf{x}_b)] \quad (1)$$

where  $\mathbf{x}_a$  is the analysis,  $\mathbf{x}_b$  is the background,  $\mathbf{P}_b$  is the background error co-variance,  $\mathbf{H}$  is forward operator,  $\mathbf{R}$  is observation error co-variance, and  $\mathbf{y}$  is the observation vector. The observation vector contains all of the temperature and sea ice observations that are within the geographic and time domains of the forecast model and update cycle.

A forward model is a method of converting a forecast grid variable to an observed variable. The forward operator in NCODA is simply a spatial interpolation of the forecast model grid to the observation location performed in three dimensions. Thus,  $\mathbf{H} \mathbf{P}_b \mathbf{H}^T$  is approximated directly by the background error co-variance between observation locations, and  $\mathbf{P}_b \mathbf{H}^T$  directly by the error co-variance between observation and grid location. The quantity  $[\mathbf{y} - \mathbf{H}(\mathbf{x}_b)]$  is referred as the innovation vector,  $[\mathbf{y} - \mathbf{H}(\mathbf{x}_a)]$  is the residual vector, and  $\mathbf{x}_a - \mathbf{x}_b$  is the increment vector.

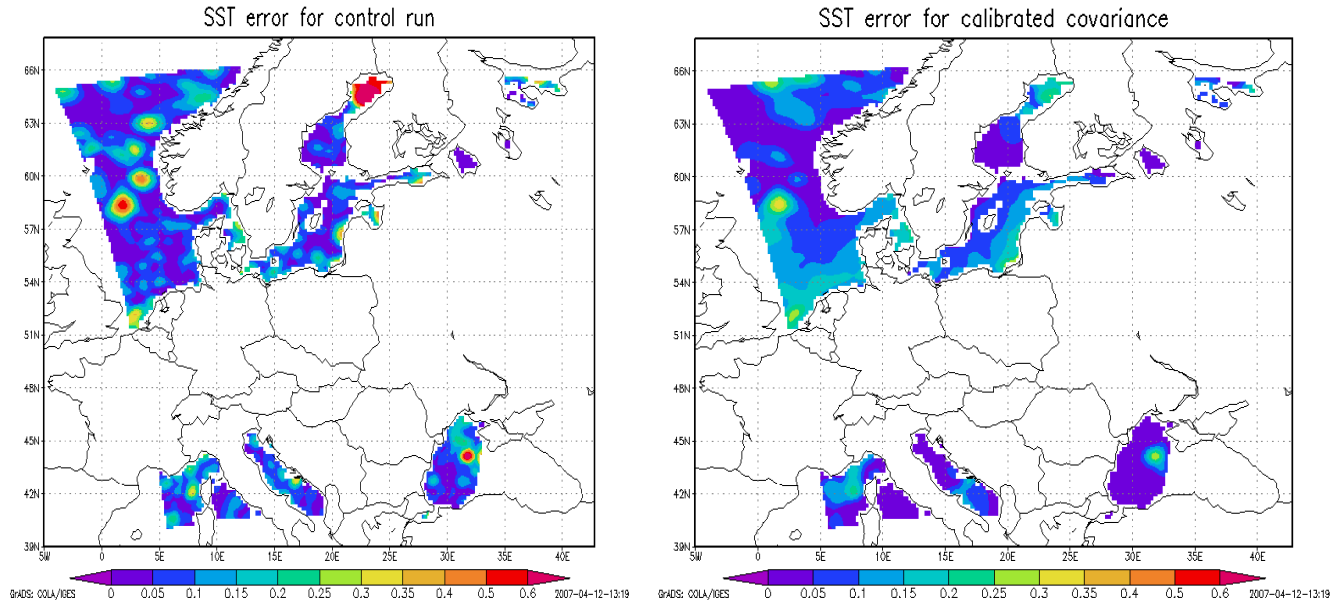
The background error co-variances are separated into a background error variance and correlation. The correlation  $C_b$  is further separated into a horizontal  $C_h$  and a vertical  $C_v$  component. All correlations are modelled as second order autoregressive (SOAR) functions.

The model error parameterisation imply a parameterisation of the innovation co-variance. We assume, that we have a co-variance model for  $\mathbf{d}$ , which has a number of unknown parameters

$$E(\mathbf{d}\mathbf{d}^T) = \mathbf{S}(\alpha) \quad (2)$$

One way to calibrate the co-variance model  $\mathbf{S}(\alpha)$  to the innovation sample  $\mathbf{d}$  is to estimate  $\alpha$  using the maximum likelihood method. For this purpose, we assume that  $\mathbf{d} \sim N[0, \mathbf{S}(\alpha)]$  for some  $\alpha = \alpha^*$  and this means that the innovation is normally distributed, zero-mean random vector whose covariance is the matrix  $\mathbf{S}(\alpha^*)$ . The conditional probability density  $p(\mathbf{d} | \alpha)$  of this random vector is given by the Gaussian density function. Given the innovation sample  $\mathbf{d}$ , the maximum likelihood parameter estimate of  $\alpha^*$  is obtained by finding the value of  $\alpha$  for which the probability density  $p(\mathbf{d} | \alpha)$  attains a maximum. This is equivalent to the minimisation of the maximum likelihood function obtained from natural logarithm of the probability density.

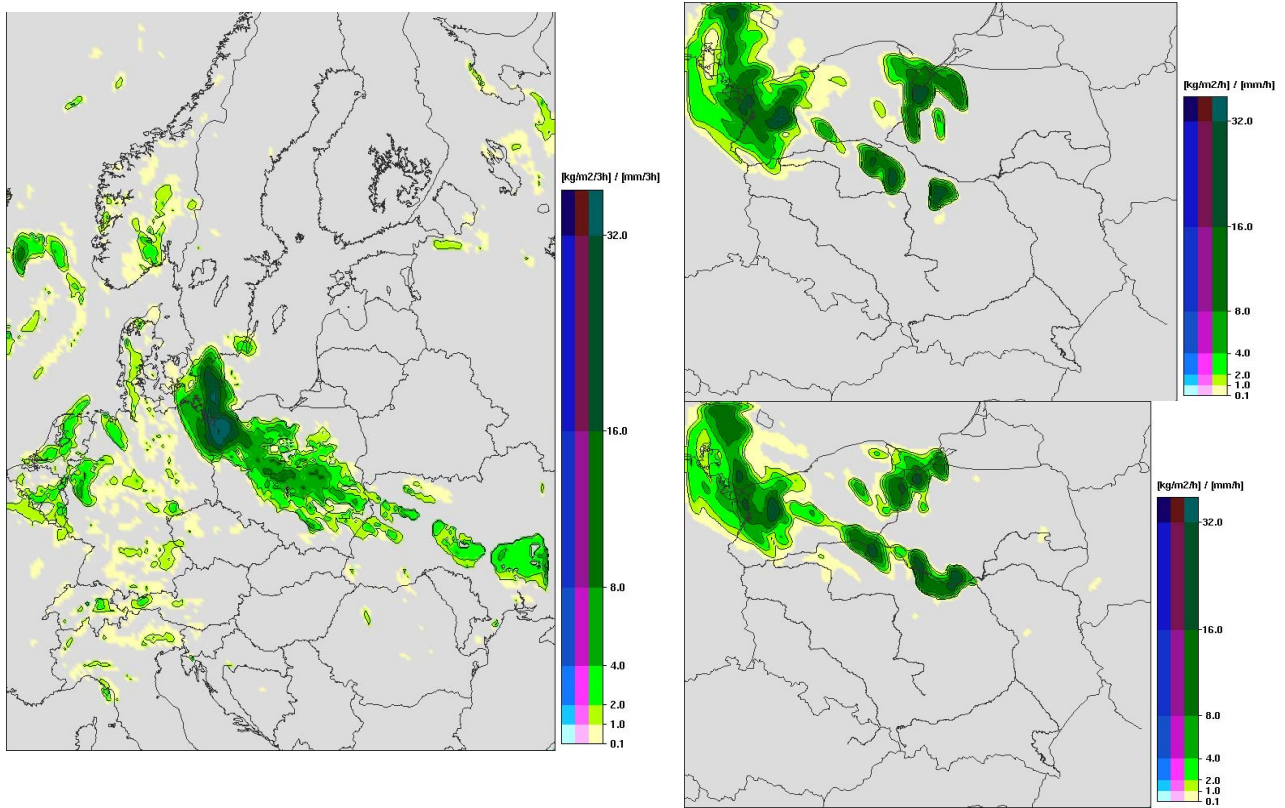
Our experiments concentrated on the estimation of the scalar parameter  $\alpha$  interpreted as a scaling factor which replace the fixed co-variance matrix  $\mathbf{S}_0$  by the parameterised co-variance  $\alpha \mathbf{S}_0$ . We improve the consistency between the covariance model used in our scheme and the actual data by multiplying the matrix  $\mathbf{S}_0$  by the scaling parameter  $\alpha$ . In our case, the analysis is made in selected sub-domains (volumes), so we implemented the method to each of volumes separately. For the grid over North Atlantic, we had 850 such volumes, for Central Europe seas we used 180 volumes. The scaling factor can be used also as a diagnostic tool, since it must be close to unity for the covariance model to be correct. Examining  $\alpha$  in the North Atlantic region, we found serious errors in data (where  $\alpha=9.3980$ ), locally destroying results of the analysis in the vicinity of this point. In control runs, these erroneous data were also assimilated, however, as the co-variance model did not follow the data closely, the impact of this error on the SST analysis was smaller.



**Fig. 2. Comparison of SST errors in the operational (left panel) and modified (right panel) version of data analysis for grid 2, Central Europe region.**

By examining the estimated SST fields for calibrated and control runs, we find that our approach produced smoother and more realistic analyses. In the case of quality controlled initial data, the errors of the analysis are smaller than those used operationally. However, the method is sensitive to the gross errors included in data, so quality control issues for this method are essential.

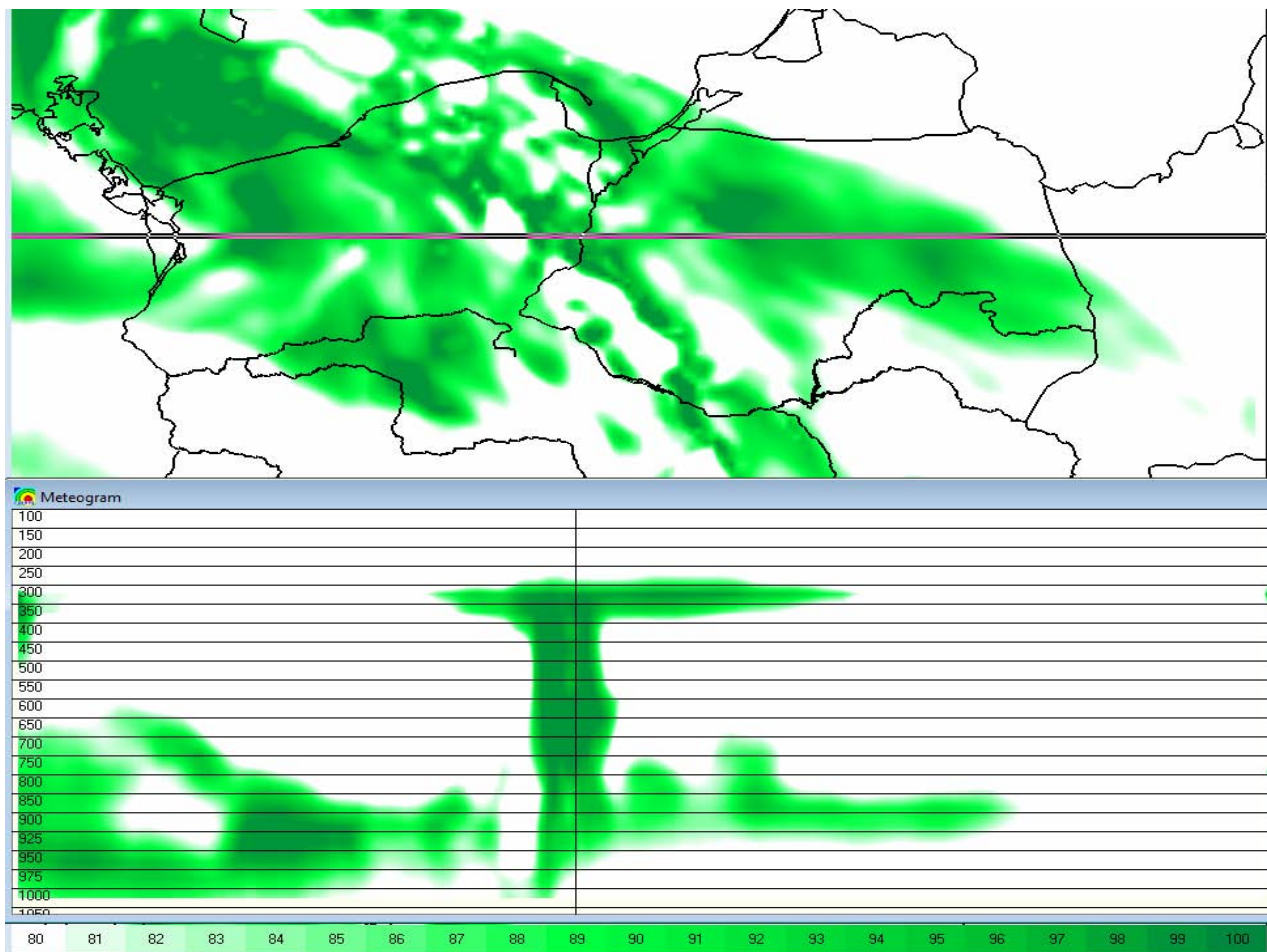
Another field of activity within this project in FY07 was the development of a entity based scheme of verification of precipitation patterns produced by the COAMPS system. From Fig. 3, it is evident that precipitation patterns estimated using parameterized convection (left panel) and explicit moist physics (right panels) differs in position and intensity. To examine the behavior of the model, we decided to work on the Ebert-McBride technique (EMT) for quantitative precipitation verification. The aim of the EMT approach is to verify to what extent the forecast entity has the same location, shape, and magnitude as the observed one, with resulting error statistics based on the properties of each entity. This type of verification utilizes a pattern-matching technique to horizontally translate the forecast entity over the observed one. The best match can be determined in a number of ways, usually by maximizing the correlation coefficient or by minimizing the total error.



***Fig. 3. Precipitation forecasts at 13 km grid (left panel) and 4 km grids (right panels) in moving frontal situation.***

We have now developed software which enables us to produce the forecasts and radar observation on common projections and with the same resolutions. The verification area is limited to the area covered by the radars (in our case, the Baltic Sea catchment). We also are able to divide the forecasts and observations into separate entities and our algorithm keeps track of the evolution of these entities. We are working on statistics such as the mean horizontal displacement of the forecast, the error in the forecast and observed rain area, main and maximum rain rates, rain volume, and the pattern correlation of the corrected forecast. Although the position of the forecast patterns is still different from the observed one, the main features of the convective systems are simulated reasonably well. The example presented on Fig. 4 comes from our 4 km run, in which explicit moist physics is used. The cross-section shows well developed cumulonimbus clouds with an anvil top.

Another field of activity within this project in FY07 was the work on an ensemble data assimilation system based on the Kalman square root filters. Ensemble data assimilation systems transform a forecast ensemble into an analysis ensemble with appropriate statistics. This can be done statistically by treating the observations as random variables, or deterministically, requiring that the covariance of the updated ensemble satisfy the Kalman filter analysis error covariance equation. We implemented the deterministic analysis ensemble update, which is a Monte Carlo implementation of the Kalman square root filters. Ensemble square root filters are not unique, since different ensembles can have the same covariance. This non-uniqueness had led to the development of several different algorithms for updating the analysis ensemble. In our implementation of the square root filter, we used the Whitaker and Hamil (2002) method.



**Fig. 4.** *Vertical cross-section trough the frontal system. 4.3 km grid over Poland, 22 Jul 2007.*

An additional processing of the ensemble covariances is introduced to avoid the filter divergence caused by sampling errors. The techniques commonly used (and implemented in our work) are distance dependent covariance localization and covariance inflation. Covariance localization is a filter that forces the ensemble covariances to go to zero at some horizontal distance  $L$  from the observation being assimilated. Covariance inflation simply inflates the deviations from the ensemble mean first guess by some factor greater than 1.0 for each member of the ensemble, before the computation of the background-error covariances and before any observations are assimilated.

## **PERSONNEL EXCHANGES AND TRAVEL COMPLEMENTED**

**Marcin Witek, University of Warsaw** – visited NRL, Monterey, CA to work with Piotr Flatau on development of aerosol parameterization in NAAPS and COAMPS models.

**Richard Hodur, NRL, Monterey, CA** – in November 2006 visited Warsaw University for two lectures on recent developments in numerical weather prediction at NRL (one lecture was presented at ICM and the second at Military Meteorological Office) and working discussions on COAMPS issues.

**Bogumil Jakubiak, University of Warsaw** – participated in EUMET/SRNWP Workshop on “High resolution data assimilation with emphasis on the use of moisture-related observations”. 21-23 March 2007, Norrköping, Sweden.

**Oskar Kapala, University of Warsaw** – in April 2007 visited NRL, Monterey, CA, to work with Keith Sashegyi on nested 3D-VAR algorithm and to discuss with Rich Hodur, Piotr Flatau and Maria Flatau the new developments in model dynamics. He discussed also with Ted Holt the possibility to implement a new land-surface scheme into COAMPS model.

**Bogumil Jakubiak, University of Warsaw** – participated in EGU General Assembly, Vienna Austria 15-20 April 2007 giving one oral and two poster presentations.

## **IMPACT/APPLICATIONS**

The operational version of the high resolution mesoscale model was implemented. This will improve 5-day forecasting for aviation and for support of Polish troops in Afghanistan and Iraq.

## **TRANSITIONS**

None.

## **RELATED PROJECTS**

**US GODAE project** – The Global Ocean Data Assimilation Experiment (GODAE) provides regular, complete descriptions of the state of the ocean and the atmosphere in support of operational oceanography and oceanographic research. We use the GODAE server data for our COAMPS predictions. The GODAE Monterey server is maintained by FNMOC and is sponsored by the Office of Naval Research (ONR).

**COST Action 731 project** – Propagation of uncertainty in advanced meteo-hydrological forecast systems. Within this action, we started to develop a radar data assimilation scheme using the ensemble Kalman filter approach.

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